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Grain yield stability of high-yielding barley genotypes under Egyptian conditions for enhancing resilience to climate change

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Identifying stable, high-yielding genotypes is essential for food security. This is particularly relevant in the current climate change scenario, which results in increasing occurrence of adverse conditions in the Mediterranean region. The objective of this study was to evaluate stability of barley (*Hordeum vulgare* L.) grain yield, and its relationship to the duration of the growth cycle and its stability under Mediterranean conditions in Egypt. Nineteen genotypes were evaluated during three growing seasons (2013–14 to 2015–16) at two locations (Elkhatara, Ghazala) and two growing seasons (2014–15 and 2015–16) at a third location (Ras-Sudr), i.e. eight environments (location–year combinations) in total. The linear regression explained a significant 48.2% and 22.8% of GEI variation for days to heading and grain yield, respectively, and the genotypic linear slopes were highly related to the first principal component of the AMMI model. Although all genotypes were well adapted to the region, there were different GEI responses, with changes in ranking across locations. Some stable and broadly adapted genotypes were identified, as well as unstable genotypes with specific adaptations. High yields across environments were attained by very stable (G4, G5), intermediate and stable (G1, G9) and highly responsive (G18, G19) genotypes. In general, responsiveness (*b* values) of yield and days to heading were negatively correlated, and high yielding genotypes showed different patterns of responses of days to heading. Genotypes G1, G4, G5 and G9 seemed best adapted overall, with longer season genotypes (e.g. G18 and G19) offering prospects to explore other formats of varieties in breeding, particularly for situations of climate instability.

Additional keywords: adaptation, biplot analysis, multi-environment trials, stability.E. Mansour *et al*.

Introduction

Plant performance is controlled by both genotypic and environmental factors. The variation that cannot be explained directly by genotypic or environmental components is considered as genotype × environment interaction (GEI) (Yan and Hunt 2001; Del Moral *et al*. 2002; Warzecha *et al*. 2011). GEI occurs when the genotypes respond differently across environments, and it is considered one of the main factors limiting progress in breeding and, hence, in agricultural production (Esuma *et al*. 2016; Cuevas *et al*. 2017). Varying responses across environments result in loss of predictive ability of future yields (Yan and Kang 2002; Hageman *et al*. 2012; de Leon *et al*. 2016). GEI can be divided into two types: qualitative (crossover) interaction, when the ranking of genotypes changes between environments; and quantitative (non-crossover) interaction, when the ranking of genotype does not change from environment to another (Singh *et al*. 1999; Brancourt-Hulmel *et al*. 2001; de Leon *et al*. 2016).

Barley (*Hordeum vulgare* L.) is one of the main winter cereal crops of Mediterranean agriculture and it is cultivated commonly in arid and semi-arid areas (Samarah *et al*. 2009). Studying the stability of barley genotypes can be done with multi-environment trials (METs), which are carried out by testing a set of genotypes over different locations and years (Yang 2007; Romagosa *et al*. 2009).

The development of genotypes with flowering time adapted to the target environment is essential in barley-breeding programs, because it affects yield potential and realised yield. Matching phenology to water supply is an essential mechanism of adaptation for dryland crops (Ludlow and Muchow 1990). Under terminal water stress, which is common in Mediterranean environments, early-heading genotypes are usually preferred over later ones, because earliness is an escape strategy (Bidinger *et al*. 1977; Sanchez *et al*. 2002; Tewolde *et al*. 2006; Mansour *et al*. 2017). However, the optimal strategy in each case will depend on patterns of stress occurrence. Therefore, yield stability could be achieved by selecting genotypes adapted to the target environment (Brancourt-Hulmel *et al*. 2001; Lijalem 2014). This is particularly relevant in the current climate change scenario. In addition to increasing average water-stress levels and overall temperatures in the Mediterranean, the occurrence of adverse conditions is expected to increase, affecting yield averages and increasing yield fluctuations (Trnka *et al*. 2014). Under these circumstances, breeding for optimising crop-cycle duration (mainly days to heading) and grain yield stability are important targets for Mediterranean conditions (Comadran *et al*. 2011; Kole *et al*. 2015).

Many statistical methods have been proposed for quantifying GEI, varying from univariate to multivariate models (Mohammadi and Amri 2013; de Leon *et al*. 2016). A widely used univariate method is joint regression analysis (JRA), because it is simple and provides useful information on the stability of genotypes (Becker and Leon 1988; Rharrabti *et al*. 2003). According to this model, stable genotypes present high yield, a slope, b, close to 1, and a deviation from regression, S^2d_i, close to zero (Eberhart and Russell 1966). The most popular multivariate methods to analyse GEI are the additive main effects and multiplicative interaction model (AMMI) (Gauch 1992; Gauch 2006) and the genotype main effect plus genotype × environment interaction model (GGE), based on a biplot analysis (Yan *et al*. 2000). AMMI is a valuable tool owing to the greater insight and more complete use of the information that it provides in GEI studies (Lacaze and Roumet 2004; Li *et al*. 2006; Yan *et al*. 2007; Yang *et al*. 2009). The objective of this study was to evaluate the overall performance and stability patterns of a set of high-yielding barley genotypes, and to measure GEI and stability for days to heading and grain yield across eight environments under Mediterranean conditions.

Materials and methods

Plant material and experimental design

Nineteen barley genotypes were used in the study, including 15 six-row and four two-row. According to their origin, eight genotypes are Egyptian varieties and the others are from the UK and ICARDA (Table 1). Genotypes G16–G19 were chosen among several other non-Egyptian genotypes tested in these experiments for their good agronomic performance. The genotypes evaluated are spring types, except Giza 123 and Giza 126, which were assumed to be of spring-growth type but recently were demonstrated to be intermediate types (winter growth habit with a low vernalisation requirement) (Mansour *et al*. 2018). These two genotypes are facultative from an agronomic point of view (they can be sown in winter or spring), but they are genetically different from facultative genotypes (as defined by Karsai *et al*. 2005), having a true vernalisation need provided by an active *VrnH2* gene and a reduced-vernalisation *VrnH1* allele. Nine of the genotypes evaluated (in addition to other five exotic genotypes) were evaluated in a companion study with focus on growth habit and adaptation (Mansour *et al*. 2018).

The 19 genotypes were evaluated in field trials during three growing seasons (2013–14 to 2015–16) at three locations in Egypt; there were eight environments (location–year combinations) because one combination was missing. Trials were carried out during three growing seasons at Elkhatara and Ghazala (two experimental farms belonging to the Faculty of Agriculture, Zagazig University), and during two growing seasons at the experimental farm of Ras-Sudr Research Station, South Sinai (Table 2). The experimental sites represent different climatic conditions. Meteorological data (total rainfall, average minimum and maximum temperatures) maintained by the Egyptian Meteorological Authority were gathered for the last 34 years (1983–2016) from stations close to the experimental sites (Supplementary materials, table 1 available at the journal's website). The three sites also represent different soil types. Soil at Ghazala is predominantly clay (48% clay), whereas it is mostly sandy at Elkhatara (94% sand) and Ras-Sudr (86% sand). Moreover, the site at Ras-Sudr is affected by salinity, in both the irrigation water (7.03 ds m^{-1}) and the soil (8.65 ds m^{-1}). See Supplementary materials table 2 for details of soil properties of the experimental sites.

The experimental design at all environments was a randomised complete block with three replications. Plots consisted of six rows, 4 m long and with 20 cm between rows. All trials were irrigated with the standard systems used at each site. Surface irrigation was used at Ghazala (~250 mm ha^{-1}, distributed across the season) and Ras-Sudr (450 mm ha^{-1}), whereas sprinkler irrigation was applied at Elkhatara (400 mm ha^{-1}). Recommended agronomic practices for application of nitrogen, potassium and phosphate fertilisers, and for pest, disease and weed control, were followed as customary for barley in each region.

Traits

Number of days to heading was scored as the time between sowing and the date when awns of ~2 cm were visible on 50% of stems in the plot. Grain yield was measured as the weight of grain harvested per plot and converted to kg per ha by taking the harvested plot area (4 m^2) into account.

Statistical analyses

Combined analysis of variance for days to heading and grain yield was performed to determine the effects of environment, genotype and GEI. Genotypes, years and locations were considered fixed factors. Additionally, the joint regression of each genotype on an environmental index (b_i), and the variance due to deviation of regression (S^2d_i) were calculated as suggested by Eberhart and Russell (1966). AMMI analysis (Gauch 1992) was performed by using SAS software version 9.1 (SAS Institute, Cary, NC, USA). AMMI's stability values (ASVs) were derived from the AMMI model as suggested by Purchase (1997):

$$\mathrm{ASV} = \sqrt{\frac{\mathrm{SS_{IPCA1}}}{\mathrm{SS_{IPCA2}}}\left(\mathrm{IPCA1}_{Score}\right)^2 + \left(\mathrm{IPCA2}_{Score}\right)^2}$$

where SS_{IPCA1} and SS_{IPCA2} are the sum of squares of the interaction explained by the first and second principal component (PC) axes of the AMMI analysis. IPCA1 and IPCA2 are the genotypic scores at the first two PC axes.

The percentage adaptability (ADP) was calculated according to St-Pierre *et al*. (1967) via the following equation:

ADP = (no. of times that genotype exceeds environmental mean/total no. of environments) ×100

The stratified ranking technique of Fox *et al*. (1990) was also used to classify the genotypes. Stratified ranking of each genotype was expressed as the proportion of environments where that genotype ranked in the top third of the entries (TOP). In this analysis, genotypes found mostly in the top third across environments were regarded as widely adapted and stable.

The correlation coefficients between genotypic AMMI scores with regression slopes and trait averages were calculated. In addition, the correlations between AMMI environmental PC scores with minimum and maximum temperatures at each environment were also calculated.

Results

Analysis of variance for both traits showed significant effects for genotypes, environments and their interaction (Table 3). Environments accounted for the largest proportion of sums of squares, 71.0% and 81.5% for days to heading and grain yield, respectively; next, GEI effects captured

17.5% and 10.1%, then genotypic effects accounted for 8.9% and 7.1% for each trait, all terms being significant. Environmental variation was clearly dominated by the location effect, which accounted for 92.2% and 92.1% for days to heading and grain yield, respectively (Table 3). Hence, for both traits, year and location × year were comparatively minor terms. Breaking down the GEI into its components revealed that genotype × location contributed the most (70.2% and 42.8% for days to heading and grain yield, respectively), followed by the three-way interaction, genotype × location × year (22.0% and 29.6% for days to heading and grain yield).

Phenotypic variation for both traits was quite large. Genotypic averages of days to heading across environments varied from 63.0 days (G16 at E7; see Table 2 for environment codes) to 108.0 days (G19 at E6), compared with the overall genotypic averages, which ranged from 86.8 (G11) to 98.6 (G19) (Tables 1 and Supplementary materials table 3). Grain yield varied from 1253 kg ha^{-1} (G6 at E8) to 7967 kg ha^{-1} (G19 at E1), compared with overall genotypic averages, which varied from 4179 kg ha^{-1} (G14) to 5864 kg ha^{-1} (G4) (Tables 1 and Supplementary materials table 4).

Joint regression and adaptability parameters

Linear regression explained a high percentage of GEI variation, 48.2% and 22.8% for days to heading and grain yield, respectively (Table 3). Regression slopes (b_i) indicate overall genotypic responsiveness to the overall gradient of variation for the trait. For days to heading, b_i varied from 0.44 to 1.51 and for grain yield from 0.74 to 1.27, revealing large differences in genotypic responsiveness across environments (Table 4). Genotypes were ordered similarly by deviations from regression (S^2d_i) and ASVs (correlation coefficients of 0.86 and 0.97 for days to heading and yield, respectively). They indicate the presence of genotypic features that depart from overall responses. Large values for these variables indicate large fluctuations of the traits (i.e. instability). In addition, there was large variation among genotypes for both parameters. For ASV, the lowest values for days to heading were presented by G2 and G8 followed by G3, G15 and G13, which indicates stability of these genotypes (Table 4). Lowest ASVs for grain yield were exhibited by G7 and G8 followed by G9, G18, G1, G12, G10, G19 and G4 (Table 4).

The adaptability parameter TOP (Fox *et al*. 1990) for grain yield indicated that G19, G4, G1 and G8 had the best performance across the highest number of trials, followed by G9, G18, G12 and G7. Parameter ADP produced similar results to TOP, with G1, G4, G7, G8, G9 and G19 showing the highest values.

AMMI analysis

The AMMI decomposition of GEI for days to heading (Table 3) found six significant components (explaining 68.3–1.7% of the sums of squares). For grain yield, there were seven significant components (explaining 43.7–1.7% of GEI sums of squares). Furthermore, it was clear that the first two PCs explained most of the GEI effect, 79.0% and 62.6% for days to heading and grain yield, respectively (Table 3).

An AMMI1 biplot was chosen for best representing the effect of each genotype and environment, as well as stability, for both variables. For days to heading (Fig. 1*a*), genotypes closer to zero on the PC1 axis indicated a smaller contribution to GEI than those further away. Genotypes G2, G3, G7, G8, G9 and G15 showed early and stable heading, followed by G5, G13, G11, G10, G1 and G4. Genotypes G12, G14, G6, G16 and G17 showed intermediate and unstable heading. Besides, G18 and G19 displayed late and unstable heading. The environments presented different contributions to the GEI, with E4, E6 and E5 (all Elkhatara trials) showing small contribution; E1, E2 and E3 (Ghazala trials) intermediate contribution; and the greatest contribution detected at E7 and E8 (Ras-Sudr) (Fig. 1*a*).

In the AMMI1 biplot for grain yield (Fig. 1*b*), genotypes G1, G4 and G9 showed high yields together with good stability, followed by G5 and G19, more unstable. By contrast, G15, G6, G2, G16 and G17 were unstable. Environments showed different contributions to the interaction, with E2, E3, E5 and E6 presenting an intermediate contribution, whereas E1, E4, E7 and E8 made a greater contribution (Fig. 1*b*). The last two environments, corresponding to Ras-Sudr, had large contributions to GEI for both variables, indicating large differences between this site and the other two sites.

The AMMI2 biplots (Fig. 2) summarise a large proportion of GEI; PC scores close to zero indicate low GEI, i.e. more stable genotype across environments. Regarding days to heading, G1, G2, G3 and G13 showed the least variable values, whereas genotypes G6, G12, G14, G16, G17 and G18 showed the largest fluctuations across environments. Environments contributing most to GEI were E6, E7 and E8, whereas there was small contribution from E4 (Fig. 2*a* and Supplementary materials fig. 1A). PC1 mostly reflected the difference between E7 and E8 and the other environments. Genotypes G6, G12, G14 and G18 were relatively later at these environments, and conversely, G1, G4, G16 and G17 were relatively earlier, compared with expectations calculated just with marginal means.

Concerning grain yield, genotypes G1, G5, G7, G8, G9, G11, G14 and G18 were more stable, all being closer to the origin than the rest of the genotypes. Some of the stable genotypes (G1, G5 and G9) also presented high average yields. Similar to days to heading, the main contrast driving PC1 was E7 and E8 (Ras-Sudr) *v.* the remaining environments (except E3), with E1 and E8 contributing the most to GEI.

Relationship among stability parameters and stability with climate

Correlation coefficients were calculated between genotypic AMMI PC scores and regression slopes for both traits. The scores of the PC1 had a very high and significant correlation with the regression slopes for days to heading (–0.95) and grain yield (0.92), meaning that AMMI score and regression coefficient can be used interchangeably. However, PC2 of each AMMI analysis did not correlate significantly with the regression slopes for both traits (0.14 and –0.28 for days to heading and grain yield respectively).

The correlation coefficient between the regression slopes of the two traits was negative (–0.42, P = 0.08), indicating that the higher slope for one trait, the lower for the other, meaning that the more responsive genotypes for grain yield were less responsive for days to heading. The correlation coefficient between genotypic slopes for grain yield and genotypic average of days to heading was 0.39 (P = 0.10), also suggesting a trend towards earlier genotypes being more stable for grain yield. However, the correlation coefficient between genotypic slopes and genotypic average for days to heading was –0.46 (P = 0.05), indicating that later genotypes were less responsive for days to heading.

The regression slopes of days to heading and grain yield were plotted against each other to examine the relationship of the responsiveness for these two traits (Fig. 3). The highest yielding genotypes, G1, G4, G5, G9 and G19, showed different degrees of responsiveness for grain yield, as indicated previously, but G1 and G9 showed a low responsiveness for days to heading and grain yield.

Correlation coefficients between AMMI environmental PC scores and minimum or maximum temperatures were calculated. PC2 did not correlate significantly with temperature; hence, only the correlation with PC1 is presented (Table 5). The analysis showed a significant negative correlation among environmental PC1 scores and minimum temperatures during December and March for days to heading. For grain yield, there were significant positive correlations of PC1 with minimum temperatures for most of the season, and with maximum temperatures only in January.

Discussion

Stability of grain yield is important to ensure cereal production, particularly under climate change and increasing adverse conditions. One of the main drivers of barley adaptation is the modulation of growth-cycle duration to match resource availability, particularly water and temperature. This was achieved particularly through adjustment of flowering time (Turner *et al*. 2005; Casao *et al*. 2011; Comadran *et al*. 2012). The main objectives of this study were to determine the extent and patterns of GEI for barley cultivation in Egypt, and to reveal possible relationships between stability of grain yield and flowering time. The results presented here, using varieties with good yielding ability, showed the presence of large GEI, which is typical of Mediterranean environments (van Oosterom *et al*. 1993; Rodriguez *et al*. 2008). Most environmental variation was due to the location effect, followed by location × year interaction. These results are in line with previous studies (e.g. Dehghani *et al*. 2006; Ceretta and van Eeuwijk 2008; Mohammadi *et al*. 2009; Mohammadi and Amri 2013; Aktaş 2016; Kebede *et al*. 2017). In addition, genotype × location presented the largest contribution of GEI, followed by the three-way interaction (genotype × location × year). The large contribution of location to the GEI opens the possibility to explore breeding of varieties for specific adaptation to each of these locations. This was expected for Ras-Sudr, because it presents a unique salinity problem, but was also observed for the other two locations. Ghazala and Elkhatara are not very different climatically, but have rather different soils, which may explain changes in genotypic rankings between these two locations.

In order to study GEI and to determine stable genotypes across different environments, it is advisable to use different statistical models, because each model provides a slightly different perspective on the data. In general, JRA, TOP and ADP are used for evaluating genotype stability owing to their simplicity. However, AMMI provides more insight to describe GEI patterns, easily interpretable in a visual manner, discriminating stable and unstable genotypes, and measuring specific contributions of each environment and genotype to the interaction, as well as identifying different mega-environments. Similar results were provided by the two principal stability methods, JRA and AMMI, as revealed by the high correlation coefficients between JRA slope and AMMI PC1. Genotypes G1, G2, G3, G5, G7, G8, G9, G13 and G15 tended to present stable days to heading, because they attained regression coefficients close to unity coupled with low S^2d_i. Furthermore, they displayed highest values of TOP and ADP and lowest values of ASV as well as a location close to the origin in the AMMI2 biplot. Genotypes G6, G12 and G14 presented low slopes with high S^2d_i; that is, their adjustment to regression was poor and they were the least responsive to the factors affecting earliness. G16 and G17 were the most unstable genotypes, with the largest slopes (highly responsive) and the highest S^2d_i values. For grain yield, genotypes G1, G4, G5, G7, G8, G9, G10, G12, G18 and G19 showed good stability across environments based on b and S^2d_i, TOP, ADP, ASV and AMMI. By comparison, G2, G3, G6, G11, G15, G16 and G17 were considered unstable. Taking into account jointly productivity and stability, some genotypes were classified as productive-stable (G1, G4, G5, G9, G18 and G19), productive-unstable (G2, G3, G6 and G12), non-productive-stable (G7) and non-productive-unstable (G11, G14, G15, G16 and G17). In this respect, the UK-bred cultivars G18 and G19 were classified as productive and stable genotypes. They were, on average, one week later than the Egyptian cultivars and showed good adaptation to the Egyptian environment. This highlights the potential of non-conventional germplasm for facing future challenges of climate change in Egypt and possibly in other Mediterranean countries. On the other hand, there were genotypes with opposite responses, such as G15, which was among the lowest yielders at Ghazala and Elkhatara and one the best at Ras-Sudr (third overall), and genotypes G2, G3 and G6, with exactly the opposite trend. These genotypes show specific responses that could be explored further for their breeding potential. The three locations (Elkhatara, Ghazala and Ras-Sudr) presented good discriminating ability for the genotypes, and rather stable patterns, and they could be used for selecting stable genotypes. This was probably due to the differences in soil structure and climate conditions. Besides, the AMMI analysis indicated that E7 and E8 (Ras-Sudr) were the most distinct environments, for both productivity and GEI patterns, compared with the other environments, included in second group.

The five highest yielding genotypes across environments (G1, G4, G5, G9 and G19) presented different positions in the graphs of regression slopes and AMMI2, indicating that high yield can be achieved through different mechanisms. Additionally, the negative correlation between JRA slopes of yield and days to heading indicates that high responsiveness in days to heading (i.e. the existence of flexibility in the mechanisms that determine cycle duration) is more frequent among less responsive genotypes for grain yield (i.e. those more resilient to environmental variations). Among these was G4, which was the best genotype overall (first at Ghazala and Ras-Sudr, fourth at Elkhatara), moreover the other good genotypes showed highly variable slopes for both traits. The genotypes that were less responsive for this trait were also among the poorest for grain yield.

Furthermore, significant correlation was found between PC1 of AMMI and minimum or maximum temperature. The climatic differences among sites were not large, although temperatures were colder overall at Ras-Sudr, and this site showed differences in soil and water salinity relative to the other two sites. Therefore, temperature and soil conditions are confounded in the explanation of GEI. However, possible differences in responses to temperature among these locations should not be ruled out and should be the subject of future research.

Conflicts of interest

The authors declare no conflicts of interest.

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Table 1. Code, origin and pedigree of the barley genotypes used

Measurements are the average of each genotype across all environments

Genotype	Code	Pedigree	Spike type	Origin	Year of release	Days to heading	Grain yield (kg ha^{-1})
Giza 123	G1	Giza 117/AO 86	6-row	Egypt	1988	86.96	5315
Giza 124	G2	Giza 117/Bahteem 52//Giza 118/FAO 86	6-row	Egypt	1992	89.46	4768
Giza 125	G3	Giza 117/Bahteem 52//Giza 118/FAO 86 (sister line to Giza 124)	6-row	Egypt	1995	89.63	4607
Giza 126	G4	Baladi Bahteem/S D729-Por12762-BC	6-row	Egypt	1995	87.06	5864
Giza 127	G5	W12291/Bags/Harmal-02	2-row	Egypt	1995	90.38	5232
Giza 128	G6	W12291/4/11012-270-22425/3/Apam/IB65//A 16	2-row	Egypt	1995	89.33	4702
Giza 2000	G7	Giza 117/Bahtim 52//Giza 118/FAO 86/3/Baladi 16/Gem. (Giza 121)	6-row	Egypt	2000	88.15	4587
Giza 129	G8	Deir Alla 106/Cel//As 46/A ths*2	6-row	ICARDA	2001	88.73	4682
Giza 130	G9	Comp.cross 229//Bce Mr/DZ 02391/3/Deir Alla 106	6-row	ICARDA	2001	88.96	5034
Giza 131	G10	Cm67-B/Centeno-/3/Row906.73/4/Glora-Bar/Comeb/5/Falcon-Bar/6/Lino	6-row	ICARDA	2001	87.33	4653
Giza 132	G11	Rihane-O5//AS 46/Aths*2″ Aths/Lignee 686	6-row	ICARDA	2006	86.75	4381
Giza 133	G12	Carbo/Gustoe	6-row	ICARDA	2011	91.83	4867
Giza 134	G13	Alando-01/4/W12291/3/Api/CM67//L2966-69	6-row	ICARDA	2011	87.42	4663
Giza 135	G14	Zarza/Bermejo/Ds4931//Gloria-Bar/Copla/3Sen/5Ayarosa’	6-row	ICARDA	2011	91.50	4179
Giza 136	G15	Plaisant/7/Cln-b/4/S.P-B/Lignee640/3/S.P-B//Gloria-Bar/Come-B/5/Falcon-Bar/6/Lino Cln-B/a/S.P-B/Lignee640/3/S.P-B//Gloria-Bar/Come-B/5/Falcon-Bar/6/Lino″	6-row	Egypt	2011	88.46	4610
CHK 9	G16	Aths/Lignee86//ACSAD68	6-row	ICARDA	–	89.08	4223
CHK 39	G17	Alanda-02/4/Arizona5908/Aths//Asse/3/F208-74/5/Alanda/3/CI088	6-row	ICARDA	–	89.11	4574
Graphic	G18	Casino/Dandy	2-row	UK	1992	96.04	4924
Pewter	G19	NFC-94-20/NFC-94-11	2-row	UK	2001	98.58	5692

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Table 2. Description of the field trials during three seasons 2013–16

Measurements are the average of each genotype across all environments

Year	Location	Code	Sowing date	Lat. (N)	Long. (E)	Days to heading	Grain yield (kg ha^{-1})
2013–14	Ghazala	E1	27 Nov. 2013	30.6°	31.6°	89.12	6211
2014–15	Ghazala	E2	12 Nov. 2014	30.6°	31.6°	93.88	5479
2015–16	Ghazala	E3	19 Nov. 2015	30.6°	31.6°	95.61	6817
2013–14	Elkhatara	E4	22 Nov. 2013	30.6°	32.3°	98.28	4662
2014–15	Elkhatara	E5	15 Nov. 2014	30.6°	32.3°	92.37	4756
2015–16	Elkhatara	E6	15 Nov. 2015	30.6°	32.3°	96.6	5527
2014–15	Ras-Sudr	E7	28 Nov. 2014	29.6°	32.7°	77.07	2476
2015–16	Ras-Sudr	E8	11 Nov. 2015	29.6°	32.7°	74.86	2621

Table 3. Analysis of variance for days to heading and grain yield of 19 barley genotypes grown at eight environments

Main sources of variation are in bold type. Other values represent different decompositions of the main sources of variation (separated by dashed lines). IPC, Interaction explained by principal components. Percentages of sums of squares (%SS) for these decompositions are referred to each main source of variation. **P* < 0.05; ***P* < 0.01

Sources of variation	d.f.	Days to heading			Grain yield		
		MS	Signif.	%SS	MS	Signif.	%SS
Genotypes (G)	**18**	**223.67**	******	**8.94**	**4 767 104.0**	******	**7.12**
Environments (E)	**7**	**4566.25**	******	**70.99**	**140 235 226.0**	******	**81.46**
Location (L)	2	14 740.08	**	92.23	452 092 999.0	**	92.11
Year (Y)	2	98.67	**	0.62	25 789 621.0	**	5.25
L.Y	3	762.08	**	7.15	8 627 114.0	**	2.64
GEI	**126**	**62.54**	******	**17.50**	**968 745.9**	******	**10.13**
Regression	18	211.0	**	48.21	1 545 383.7	**	22.79
Deviation	108	37.8	**	51.79	872 639.6	**	77.21
G.L	36	153.56	**	70.15	1 449 719.0	**	42.76
G.Y	36	17.16	**	7.84	935 949.0	**	27.60
G.L.Y	54	32.11	**	22.01	669 962.0	**	29.64
IPC1	24	224.08	**	68.25	2 224 395.3	**	43.74
IPC2	22	38.41	**	10.72	1 047 811.6	**	18.89
IPC3	20	40.30	**	10.23	772 751.4	**	12.66
IPC4	18	27.28	**	6.23	714 716.4	**	10.54
IPC5	16	11.94	**	2.42	511 857.1	**	6.71
IPC6	14	9.36	*	1.66	501 760.2	**	5.75
IPC7	12	3.17		0.48	174 196.9	**	1.71
Residual	**304**	**3.80**		**2.57**	**51 087.9**		**1.29**
Total	**455**	**98.96**			**2 648 455.3**		

Table 4. Estimated stability parameters of days to heading and grain yield for 19 spring barley genotypes tested in eight environments

b, Regression slope; TOP, top third of the entries; ADP, percentage adaptability; ASV, AMMI stability value

Genotypes	Days to heading					Grain yield				
	b	S^2d_i	TOP	ADP%	ASV	*b*	S^2d_i	TOP	ADP%	ASV
G1	1.17	3.44	55.13	75.0	1.63	0.98	172 182	75.00	75.0	14.55
G2	1.07	2.27	56.45	75.0	0.97	1.24	407 359	44.74	50.0	36.71
G3	0.95	2.47	54.61	75.0	1.20	1.26	344 823	42.76	50.0	29.66
G4	1.45	11.36	42.11	62.5	4.68	0.90	186 216	88.16	75.0	21.47
G5	0.81	4.55	55.92	62.5	2.49	0.80	225 952	49.34	50.0	27.27
G6	0.54	15.76	32.24	50.0	5.02	1.27	515 794	45.39	62.5	42.41
G7	0.88	4.89	42.76	62.5	1.80	1.00	124 824	51.32	75.0	5.52
G8	0.96	3.47	67.89	75.0	1.13	0.99	138 311	71.05	75.0	10.81
G9	0.86	11.44	44.74	50.0	1.83	1.06	182 853	65.13	75.0	13.12
G10	1.21	13.30	38.16	62.5	3.42	1.10	169 064	46.71	62.5	16.83
G11	1.39	5.17	42.11	50.0	2.84	0.81	351 120	36.18	50.0	21.93
G12	0.44	9.06	36.84	62.5	5.53	1.14	160 376	55.92	62.5	16.73
G13	1.2	4.01	55.92	75.0	1.59	0.85	202 959	44.74	50.0	26.69
G14	0.44	8.70	41.45	62.5	5.55	0.88	240 802	23.03	50.0	22.18
G15	0.94	4.31	67.24	75.0	1.28	0.74	542 460	43.42	37.5	47.03
G16	1.51	29.99	55.26	62.5	6.64	0.78	290 681	25.66	37.5	28.36
G17	1.44	34.66	50.66	62.5	6.14	0.89	372 330	39.47	50.0	29.92
G18	0.88	8.38	52.84	62.5	5.47	1.14	171 632	61.18	62.5	13.42
G19	0.86	10.20	56.05	75.0	2.43	1.17	118 429	90.13	75.0	20.98

Table 5. Correlation coefficients between the first environmental principal components (PCs) of the AMMI model and trial minimum and maximum temperatures

*P < 0.05; **P < 0.01; n.s., not significant

Covariable	Month	Days to heading		Grain yield	
		PC1	Signif.	PC1	Signif.
Av. min. temp.	Dec.	–0.76	*	0.45	n.s.
	Jan.	–0.38	n.s.	0.71	*
	Feb.	–0.41	n.s.	0.60	n.s.
	Mar.	–0.74	*	0.72	*
	Apr.	–0.32	n.s.	0.55	n.s.
Av. max. temp.	Dec.	–0.08	n.s.	0.09	n.s.
	Jan.	–0.45	n.s.	0.78	**
	Feb.	–0.36	n.s.	0.07	n.s.
	Mar.	–0.82	*	0.45	n.s.
	Apr.	–0.51	n.s.	0.13	n.s.

Fig. 1. AMMI1 biplot for (*a*) days to heading and (*b*) grain yield against principal component (PC1) scores of 19 barley genotypes (G) evaluated in eight environments (E) in Egypt.

Fig. 2. AMMI2 biplot for (*a*) days to heading and (*b*) grain yield of 19 barley genotypes tested in eight environments. Numbers without prefixes are genotypes; E, environments (as presented in Table 4); lines are environment vectors.

Fig. 3. Genotypic slopes derived from the joint regression analysis: days to heading on the *y*-axis *v.* grain yield on the *x*-axis.